

Optics-Only Calibration of a Neural-Net Based Optical NDE Method for Structural Health Monitoring

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Summary

A calibration process is presented that uses optical measurements alone to calibrate a neural-net based NDE method. The method itself detects small changes in the vibration mode shapes of structures. The optics-only calibration process confirms previous work that the sensitivity to vibration-amplitude changes can be as small as 10 nanometers. A more practical value in an NDE service laboratory is shown to be 50 nanometers. Both model-generated and experimental calibrations are demonstrated using two implementations of the calibration technique. The implementations are based on previously published demonstrations of the NDE method and an alternative calibration procedure that depends on comparing neural-net and point sensor measurements. The optics-only calibration method, unlike the alternative method, does not require modifications of the structure being tested or the creation of calibration objects. The calibration process can be used to test improvements in the NDE process and to develop a vibration-mode-independence of damage-detection sensitivity. The calibration effort was intended to support NASA's objective to promote safety in the operations of ground test facilities or aviation safety, in general, by allowing the detection of the gradual onset of structural changes and damage.

Introduction

NASA has supported work to promote safety in the operation of ground test facilities or aviation safety, in general. For that purpose, it was recognized that there is value in being able to detect the gradual on-set of structural changes or structural damage in a turbo-machine component or other structural components. Such changes can occur when the component is operated outside its design envelope, where said operation might occur frequently in a ground-test facility. Or changes might occur for unforeseen reasons in a component being tested or operated normally.

Neural-net processed electronic holography was developed at Glenn to meet the NASA objective of damage detection.¹⁻³ It has been known for many years that holographic interferometry is a sensitive non destructive technique for detecting structural damage.⁴ Electronic or television holography has enabled efficient and rapid recording of the necessary holograms.⁵ There are commercial television holography systems available. Artificial neural networks can be trained to inspect the holography-recorded interference patterns and detect very small changes in those patterns, thereby automating what was previously a visual inspection technique.

The objective of the work reported herein was to calibrate or measure the sensitivity of the neural-net inspection technique. But the method reported in this paper is an optics-only calibration procedure. Another approach to calibration has been reported elsewhere.³ Both approaches require that a neural net be trained to be very sensitive to changes in a characteristic pattern or mode shape generated by time-average holography. Figure 1 shows an example of a characteristic pattern of a vibrating compressor blade. A finite element model of that blade is described later for a test.

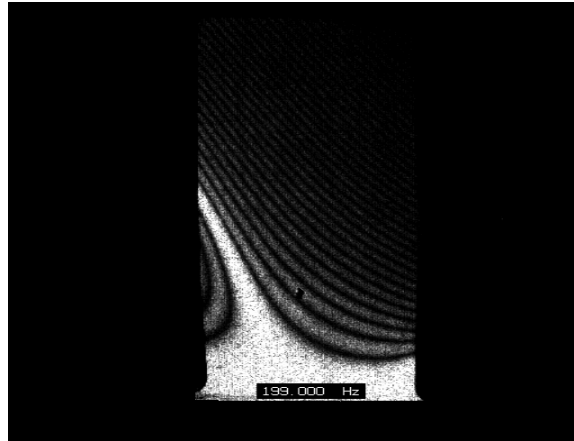


Figure 1.—Characteristic pattern or vibration mode shape of a vibrating blade (first mode).

The other approach to calibration³ is only partly optical and requires that the output of the neural network be correlated with the outputs of sensors normally used for vibration testing. Those sensors include accelerometers, strain gauges and displacement gauges of various kinds. Many of those sensors are intrusive and change the properties of the structure that they monitor. Furthermore, it is difficult to install enough of the sensors to match the coverage of the neural-net inspection technique. The current version of the neural-net inspection technique can handle up to 10,000 pixel channels covering the object to be tested or parts of that object. The other approach also requires that the object be changed in a controlled manner to change the vibration properties. The controlled process in use currently is to change fastener torques to change the mode shapes for correlation of holographic and sensor measurements. One advantage of the general version of the alternative approach to calibration is that specific kinds of damage can be induced in a calibration object to measure the sensitivity to that kind of damage. The alternative technique is not discussed in any detail in this report.

The optics-only calibration technique does not require that the object be changed and is completely non invasive. The technique is self-referencing (a null method) as are the best optical-system test methods. In effect, the vibration mode shapes of the undamaged structure are the standards against which subsequent mode shapes are compared by the trained neural network. The sensitivity of the trained net is disclosed definitively, because the output of the trained net is noted as a function of the amplitude of a contaminating mode. The amplitude of the contaminating mode is measured optically using a heterodyne interferometer. The reference mode and the contaminating mode are excited independently using sirens, eddy current exciters, or piezo-electric shakers.

The optics-only calibration technique enhances three features of the neural-net non-destructive-evaluation (NDE) method. First, as will be shown, it allows the adjustable sensitivity of the method to be matched easily to the measurement environment. The environment has various sources of noise including vibrations, air currents and other optical-path fluctuations that determine the maximum useful sensitivity. The effect of an improvement in the measurement system can easily be quantified by noting the measured improvement in the sensitivity. Second, the optics-only calibration technique is easily, although imperfectly, simulated with finite-element and optical models. Hence, a structural-design prediction can be compared with the actual whole-field measurement. Third, any mode-shape dependence of the sensitivity of the NDE method can be measured and possibly eliminated. Then the method will be sensitive to wherever structural damage occurs.

This report begins with some background on how neural nets are trained to be sensitive to changes in the characteristic patterns or mode shapes of a vibrating structure and how the training properties are exploited for calibration. The theoretical elements discussed are the basis for model training; hence there is a section that develops the performance of optics-only calibration from models. An advantage is that environmental noise does not affect the performance from model data so that a full range of sensitivities

can be investigated. Next, this report discusses the performance of the optics-only calibration method for experimental data. The effect of laboratory noise is demonstrated. The sensitivity can depend on the location of damage, if training is not correct; hence the requirements for having a single representative calibration curve are discussed. The concluding remarks section suggests how the neural-net inspection and calibration processes might be improved for customer service. The background of the neural-net inspection technique is discussed next.

Background

The neural-net NDE method is used to detect small changes in mode-shape patterns such as shown in figure 1. Equation (1) represents an ideal pattern recorded of a vibration mode using a two-frame version of electronic holography.⁶

$$J_0\left(\frac{2\pi}{\lambda} \vec{K} \bullet \vec{A}\right) 4 \operatorname{Re}(R^* a_1 v) T \quad (1)$$

The Bessel function of the first kind encodes the useful information. The wavelength of light is denoted by λ . The vector $\mathbf{A}$, denoted as bold or with an arrow, is the vibration amplitude vector. The vector $\mathbf{K}$ is the optical sensitivity vector and is defined at each point on the object. The sensitivity vector is the vector difference between the direction of the reflected ray passing through the center of the entrance pupil of the television camera and the direction of the incident ray at the object point. Unit vectors are used to define directions. The terms following the Bessel function constitute a random variable responsible for the laser speckle effect. Here, R is a complex reference-beam amplitude and $a_1 v$ is a complex object-beam amplitude. The exposure time for time averaging is denoted by T and is long enough to record several cycles of vibration. Experience has shown that four cycles are desirable.

Equation (1) is not likely to correspond exactly to an experimentally recorded pattern. Non-linearity can spoil the assumption of sinusoidal vibrations. The reference-to-object path length and phase profile can fluctuate for several reasons including air-density fluctuations, optical system fluctuations and laser mode hops. Additional vibration modes, and particularly the first vibration mode, may be excited with randomly varying amplitudes. The amplitude of the mode being monitored might fluctuate. The object-illumination profile, camera sensitivity profile and beam intensity can vary spatially and in time. The equation can be combined with a finite element model to estimate a vibration mode shape, but manufacturing variations may cause the measured and calculated modes to differ, even if the finite element model is correct.

Nevertheless, eq. (1) will be used to generate training sets to estimate the sensitivity variation and best sensitivity of a trained net in the next section. But, actual training and testing with experimental data may include all of the extraneous effects mentioned above. It has been argued⁶ that feed forward artificial neural networks can learn to handle random variations, given enough training examples. It has, in fact, been proven that the neural networks can be trained to handle the laser speckle effect and timing fluctuations in double-exposure holography. The current software neural nets are able to process perhaps as many as 10,000 input pixels. The full-size characteristic patterns contain about 640×486 pixels and are sub sampled randomly to record uncorrelated speckle patterns. The neural net will learn to ignore the laser speckle effect, provided that the net is trained with uncorrelated speckle patterns equal in number to about ten percent of the number of input pixels for each mode used for training. Hence, 10,000 input pixels would necessitate about 1,000 uncorrelated speckle patterns per mode.

All of the implementations of the optics-only calibration procedure require the simultaneous excitation of two modes at some point in the procedure. The ideal characteristic pattern for two sinusoidal modes is proportional to the expression listed as eq. (2).⁷

$$J_0\left(\frac{2\pi}{\lambda}\vec{K}\cdot\vec{A}_1\right)J_0\left(\frac{2\pi}{\lambda}\vec{K}\cdot\vec{A}_2\right) \quad (2)$$

Equation (2) is correct, if the frequencies of the two modes are irrationally related.⁷ There are, of course, “more” irrational frequency relations in the frequency bands of two modes than rational ones. The case where the two modes have the same frequency, or frequencies with an exact integer relationship, is complicated and not assumed for calibration. Equation (2) represents an ideal situation, and the same caveats apply as for eq. (1).

There are two implementations of the optics-only calibration procedure.

The training procedure for the first implementation is identical with the oldest version of neural-net-processed holography at Glenn.¹ Multiple vibration modes of the object of interest are identified using television holography. Several are selected and sub sampled to record enough uncorrelated speckle patterns. One mode is chosen as the mode to be monitored for NDE. The others are selected as examples of “different” patterns. The excitation amplitudes are comparable and typically are one, two, or a few wavelengths peak-to-peak. The modes are separated into two classes for training. The mode-to-be-monitored for NDE is placed in a class by itself. The other modes are placed in a second class. On occasion, neural-net training requirements necessitate that the second class be broken up into sub classes.

It was recognized that the sensitivity of the net to specific kinds of structural changes might depend on the mode selection. That meant that the pre-calibration applications of the NDE technique required that the mode mix be selected by trial and error. One objective of the optics-only calibration technique was to eliminate this form of mode dependence.

A feed forward neural network was trained with the two classes. Figure 2 shows the process schematically. The sub-sampled patterns are used as inputs to the net. Practical sub-sample sizes will range from 1,000 to 10,000 pixels. Each training class requires about three hidden-layer nodes, so two training classes require six hidden-layer nodes. On some occasions, sub classes require more hidden-layer nodes. The training output of the net is a simple index known as the Degradable Classification Index (DCI). One set of output values is selected for the mode to be monitored, and another set is selected for the other modes. A typical pair of outputs for the mode to be monitored for NDE is given by {0.8, 0.2}. All the other modes used for training are assigned the pair {0.2, 0.8}. The large number 0.8 for the mode-to-be-monitored is called the DCI. The DCI output of the trained net will decrease when the monitored mode shape changes for any reason that the net has not learned to ignore. The objective of course is to detect structural changes such as cracking or de-bonds. Figure 3 shows the DCI as a function of the settings of a fastener torque for one object tested. Changing fastener torques is one way to simulate structural damage.

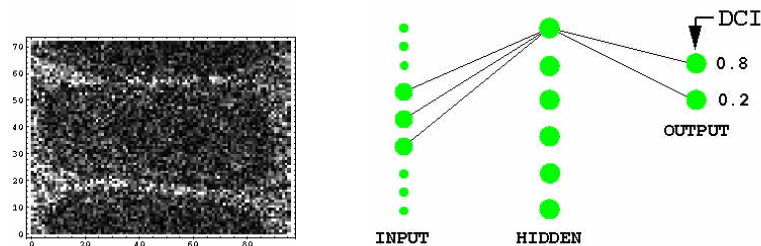


Figure 2.—Schematic of process for training neural network with sub-sampled characteristic pattern.

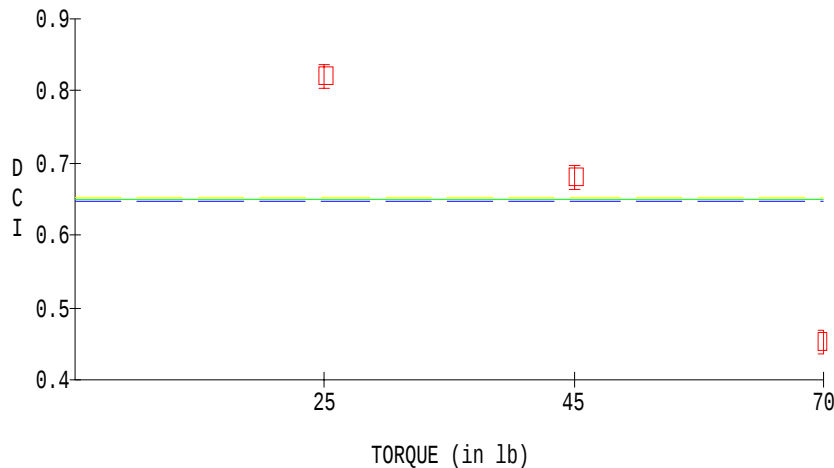


Figure 3.—Variation of neural-net output or DCI with fastener torque.

In the actual optics-only calibration process, a second contamination mode is excited intentionally, and the DCI is noted as a function of the contamination- mode peak-to-peak amplitude. A mode is preferable that has not been used for training; since it is desirable to measure mode-independent sensitivity. Repeated measurements are used to establish statistical confidence. The sensitivity is declared to be the peak-to-peak excitation where the DCI differs significantly from the zero excitation value.

The value of this approach to both calibration and NDE depends on an assumption. The assumption is that the net responds to an actual shape change of the vibration pattern rather than a simple amplitude change. Experience has shown that the net is insensitive to amplitude changes of the mode being monitored, when compared with other changes. But the net is not completely insensitive to amplitude changes, and it is desirable to hold the excitation amplitude as constant as possible. Also, the zero-amplitude condition is often included in the second training class, so that very low amplitudes tend to have low DCI values.

Two modes are excited simultaneously for training the net for the second implementation of the optics-only calibration technique. The mode to be monitored for NDE is excited at normal levels of a few wavelengths of light, and by itself constitutes one training class. The other modes are then added, one at a time, to the mode to be monitored to form the members of the other training class. Equation (2) represents the ideal pattern that results from the simultaneous excitation of the two modes. The amplitudes of these contamination modes can be varied to control the final sensitivity, and amplitudes of a fraction of a wavelength of light can be used to generate high sensitivity. The calibration curve is generated in exactly the same way as for the first implementation. A contamination mode is added in increasing amounts, and the output of the trained net is noted. Again, it is desirable to use a mode for calibration different from the modes used for training. Then, the objective is to try to quantify the mode-independent sensitivity of the trained net. The key assumption is that a net whose response does not depend on the contaminating mode will be sensitive to damage wherever it occurs.

The feasibility of the optics-only calibration process is most easily demonstrated using model generated data. Equations (1) and (2) are combined with a finite element model of a structure and a model of the electronic holography process for this purpose. The various sources of extraneous random and systematic effects, with the exception of the laser speckle effect, need not be included; hence, the limiting sensitivity of the neural-net-processed holography method can be estimated. The next section discusses the results of the model generated tests of the optics-only calibration process.

Model-Generated Tests

A finite element model of a compressor blade was used for these tests.⁸ The model and the corresponding blades were used in the past for various tests of the neural-net techniques. Figure 4 shows the finite element grid and a photograph of an actual blade. The grid permits the displacement vector of a computed mode to be specified at 903 locations. There are 21 chord wise and 43 span wise coordinates in the grid. Hence, 903 inputs to the neural network can be calculated without interpolation. Subsequent work has shown that it is desirable to have at least 2,000 inputs for a measured structure, so 903 inputs have marginal value.

A sensitivity vector $\mathbf{K}$ must be computed to be combined with the displacement vector $\mathbf{A}$ for each mode to form the arguments of the Bessel functions in eq. (1) and (2). The sensitivity vector was computed for this test for one optical arrangement used to view the actual blades. The maximum reduction in the effect of $\mathbf{A}$ in the arguments of the Bessel functions was about 11 percent for the first mode. Highly twisted blades can exhibit much larger reductions.

Finally, the laser speckle effect must be introduced. Random number generators were used with a model of the laser speckle effect to assure that there were enough uncorrelated speckle patterns per mode (at least 91 for the 903 elements).

Figure 5 shows computed characteristic patterns for the first 8 computed modes. Only the first 6 modes resembled the modes actually measured. The first mode can be compared with figure 1.

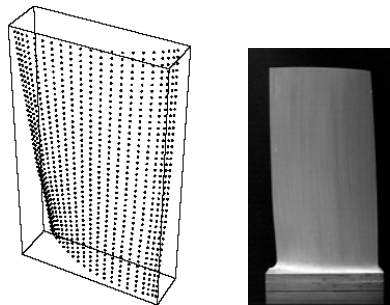


Figure 4.—Finite element grid and corresponding model blade used for model-generated tests.
Figure 1 shows the first characteristic pattern.

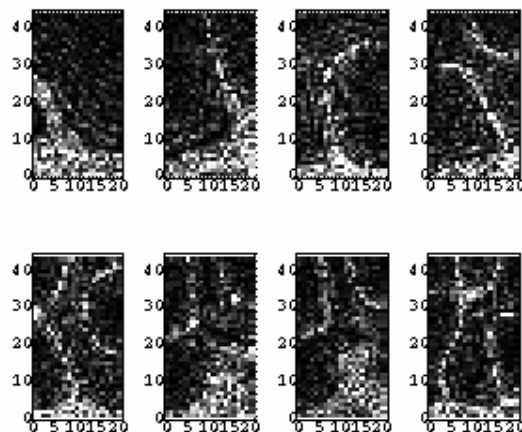


Figure 5.—Model-generated characteristic Patterns for blade in figure 4.

Simulation of First Implementation of Calibration Procedure

The first implementation of the optics-only calibration procedure was tested for four combinations of the modes in figure 5. They are listed by combination number.

Number	Monitored mode	Other modes for training	Contamination mode
1	4	2, 3, zero	5
2	4	2, 3, zero	6
3	3	2, 5, zero	2
4	4	2, 3, zero	2

Here “zero” refers to the zero-amplitude condition (speckle pattern only). The “Other modes for training” constitute the second training class defined above; whereas the monitored mode forms the first training class. Note that the contamination mode used for calibration differs from the training modes for combinations 1 and 2, but is the same as one of the training modes for combinations 3 and 4.

The peak-to-peak amplitudes of all the nonzero training modes were six waves. The wavelength was 532 nm, so that the peak-to-peak amplitudes were 3192 nm. This amplitude is at the upper extreme for small-amplitude training. Large-amplitude training has been tested, but not for calibration. The neural net for combinations 1, 2, and 4 was trained to a root-mean-square error of 0.0039. The neural net for combination 3 was trained to a root-mean-square error of 0.0039 also. The overall root-mean-square error is evaluated for all training inputs.

For testing, the contamination modes were added to the monitored modes with peak-to-peak amplitudes of 10, 20, 40, 80, 160, 320, and 640 nm. One hundred uncorrelated speckle patterns were generated for each amplitude. The test speckle patterns are uncorrelated with the training speckle patterns.

The calibration curves were computed as un-weighted simultaneous comparisons of means (ANOVA ONEWAY). Figure 6 presents the results for combinations 1 and 2.

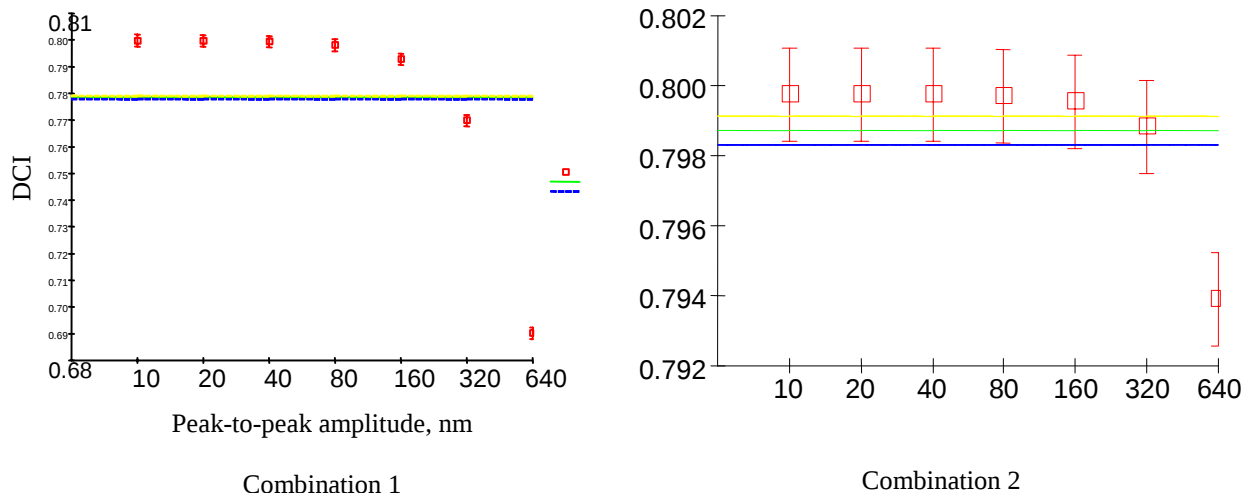


Figure 6.—Calibration curves for two contamination modes when mode 4 is monitored.

Discussion of Results for the First Implementation

The sensitivity observed in figure 6 is at best about 160 nm peak-to-peak. The sensitivity is low. The current recommendation is to use about 2,000 inputs; whereas this simulation uses only 903. The sensitivity also depended on the mode mix used for training and calibration. The sensitivity is worse than 320 nm for combination 2. The decision for the experimental work presented later was to increase the number of training modes in order to eliminate the mode-dependence of the sensitivity. The observed mode dependence of sensitivity confirms early observations of that effect.¹

Simulation of Second Implementation of Calibration Procedure

The sensitivity, in the absence of the laboratory noise sources, is easy to increase greatly. The test of the first implementation showed a best peak-to-peak sensitivity of 160 nm. The objective of the second implementation was to make the net sensitive in the peak-to-peak amplitude range from 0 nm to 80 nm.

Earlier work with model-induced cracks in the blades represented by figure 4 and in cantilevers showed that a net could be trained to detect crack-induced changes in the vibration-amplitude distribution of as little as 10 nm.² Such sensitivities can be achieved by transforming the characteristic patterns prior to training and detection. The transformation is called folding^{2,9} and is an intensity dependent transformation applied to the speckled characteristic patterns such as modeled by eq. (1).

To understand folding, note that eq. (1) admits both positive and negative values. Hence, actual imaging on a computer monitor requires that this pattern be combined with an offset or that its absolute value be evaluated. The absolute value operation transforms the negative values from eq. (1) into positive values. Figure 7 shows this transformation pictorially. The original data have, in a sense, been folded about zero. This process can be generalized. Data between any two values can be transformed into the full positive intensity range. That range might be 0 to 1 for the input of a feed forward neural network or 0 to 255 for an 8-bit imaging system. Figure 8 shows 3 folds resulting in 4 ranges being transformed. This technique was discovered to greatly increase the sensitivity of a neural net to changes in the characteristic patterns. Folds need not be placed uniformly, but uniform placing is reported herein. The transformation can be chosen to maintain normal contrast beginning at zero or to reverse it. This report presents only normal contrast. Experience has shown that increasing the number of folds beyond the point that the net first learns the training set is not beneficial and can actually degrade performance.

Another effect of folding is that it may effectively increase the number of training classes and therefore the number of hidden layer nodes required to learn the training set.

The fourth mode in figure 5 was selected as the mode to be monitored for NDE purposes. It was excited as before at 6 waves peak-to-peak. The training set consisted of the fourth mode and the fourth mode combined with 80 nm peak-to-peak excitations of the second and third modes. The fourth mode by itself was assigned one output index {0.8, 0.2} and the combined modes were assigned the opposite index {0.2, 0.8}.

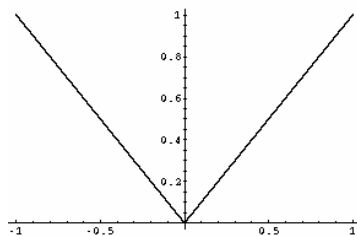


Figure 7.—One fold or absolute value.

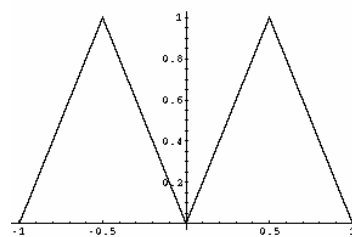


Figure 8.—Three folds.

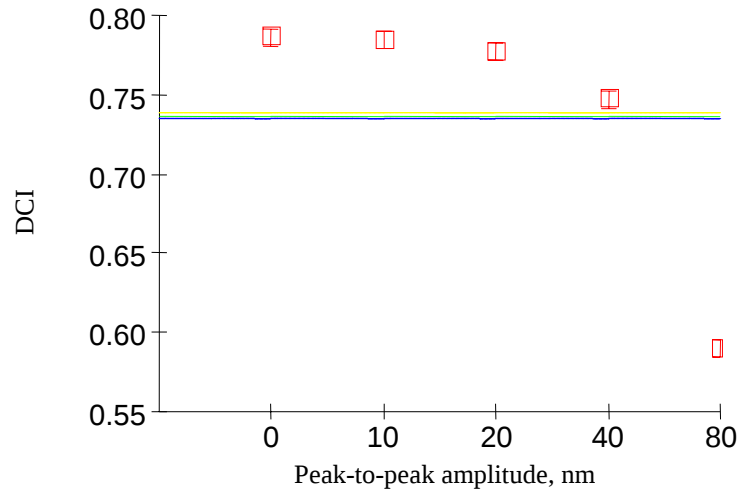


Figure 9.—Calibration curve for folded data and sixth mode contamination.
Compare with combination 2 in figure 6.

Training a net was difficult. It was necessary to use 9 folds. Furthermore, it was necessary to place the 3 mode-combinations in separate classes and to use 9 hidden-layer nodes. Learning finally succeeded yielding a training error of 0.0235. That error was about an order of magnitude larger than the error for the test of the first implementation.

The calibration procedure was then simulated by contaminating the fourth mode separately with the second, fifth and sixth modes. Note that the second mode was used in training. The data of course must be folded as before for presentation to the trained net. Figure 9 shows the results of this simulation for sixth-mode contamination corresponding to combination 2 above. Although training occurred at 80 nm, results were measured for contaminations of 10 nm, 20 nm and 40 nm as well.

Discussion of Results for the Second Implementation

Figure 9 shows that the sensitivity has increased greatly. All cases (second, fifth and sixth modes), in fact, showed a detection sensitivity of about 20 nm peak-to-peak or a vibration-amplitude detection sensitivity of about 10 nm. The noise of the responses is about equal to the training error of the neural network. The training error of the neural network is associated with the laser speckle effect.

The model-generation software can be modified to simulate various systematic and random effects. It might be expected that the 10 nm to 20 nm sensitivity is the limit when all extraneous effects are eliminated or adequately included in training.

A laboratory test was done to measure the performance of optics-only calibration in the existing laboratory.

Experimental Tests of Calibration

Experimental Setup

The same object was used for the experimental tests of the optics-only calibration method as was used for the point sensor correlations of the alternative calibration method. Figure 10 shows the setup. The object is an aluminum plate held in two vise-grip mounts, each tightened with four screws. The vise-grip

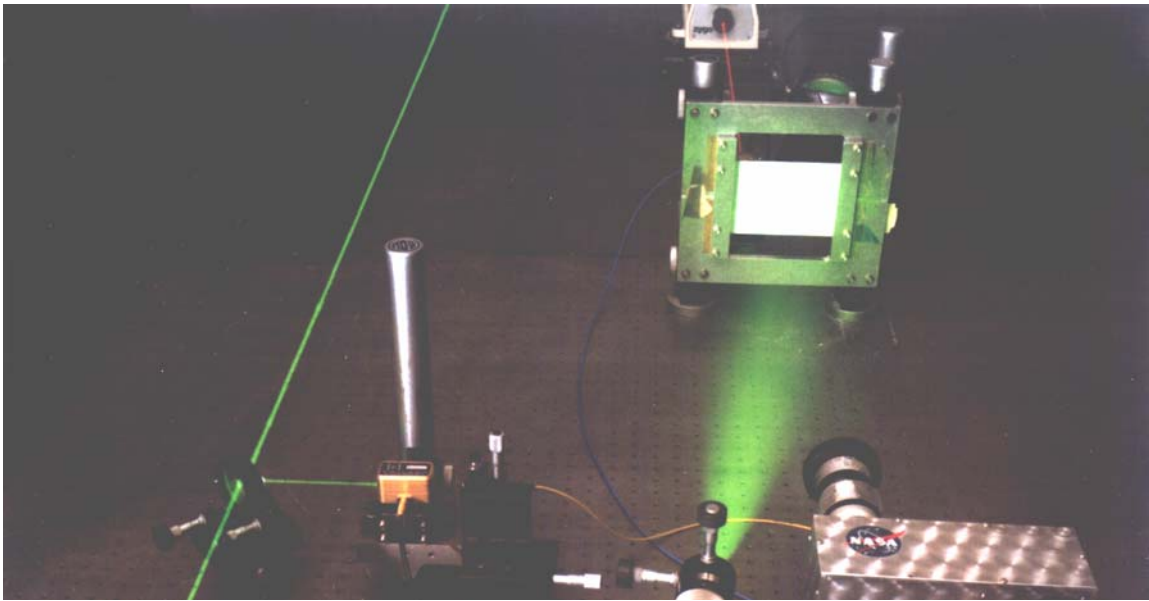


Figure 10.—Setup for experimental calibration test.

mounts themselves are not inspected during the tests. Only the visible portion of the aluminum plate is observed. That portion is 138.07×102.55 mm. The thickness of the plate is 1.24 mm. The screw torques are 70 in lb. The torque of the second screw from the top on the left is varied for the sensor correlation, but is fixed for the optics only calibration. The torque of that screw was set to 25 in lb to establish exactly the same conditions as used for the alternative calibration.

The plate modes were excited using a siren and eddy current exciters. Hence, two modes could be driven simultaneously. The vibration amplitude was measured using a heterodyne interferometer. The laser of the interferometer can be seen in back of the plate in figure 10. The interferometer can achieve 10 nm sensitivity. The interferometer head could be moved horizontally to measure the vibration amplitudes of modes having their maximum amplitudes along a scan line midway between the top and bottom of the plate. The interferometer was not particularly convenient to use for measuring vibration amplitudes at multiple points. An alternative should be sought for customer service calibrations.

The sub-sampled training patterns were recorded automatically under the guidance of software, after the plate dimensions and location had been measured in pixel coordinates in the camera image. A fresh pair of holograms was recorded for each pattern. The full-resolution pattern was divided into a grid, and pixels were recorded at random coordinates within the grid tiles. The grid tiles are not necessarily uniform in size, but the tiles were uniform for this test. The acquisition of a fresh full-resolution pattern for each sub-sampled pattern allowed the net to be presented with other laboratory fluctuations. The intent is that the net learn to ignore these fluctuations. Limited studies have been performed to test this expectation. But, various fluctuations are always present. Air currents in the room fluctuate. The first vibration mode contaminates the mode shapes at levels varying from 10 to 50 nm or more peak to peak. The amplitudes of the driven modes fluctuate. The laser spectrum occasionally varies as evidenced by a change in contrast of the fringe patterns. There are fluctuations of the electro-optic phase shifter used to step the phase of the reference beam. It is likely that there are phase fluctuations and beam pointing variations in the illumination optics. There are temperature fluctuations of the object and the optics.

The training procedure for the first implementation of the calibration technique is of course identical with the normal training procedure for the NDE technique. Figure 11 shows the first 6 vibration modes of a copper version of the plate. An early test of the calibration technique was performed by training on zero amplitude and the second, third and fourth modes. The fourth mode was selected for monitoring and excited at 750 nm peak to peak. A test using the sixth mode for contamination showed a very poor sensitivity of 320 nm peak to peak.

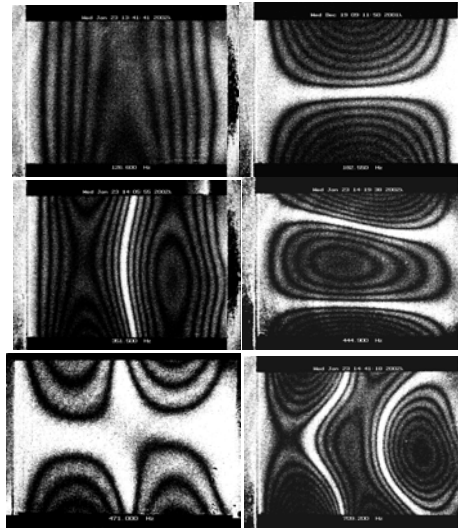


Figure 11.—First six vibration modes for experimental test of calibration technique.

The conclusion was that too few modes were being used for training, and the number of modes was increased considerably in an attempt to achieve mode-independent sensitivity.

Test of the First Implementation of the Optics-Only Calibration Technique

The plate was adjusted to have the same setup as used for calibration with sensors. All screws except for the second from the top on the left of figure 10 were adjusted to 70 in lb, and the second screw from the top was adjusted to 25 in lb. The first ten modes were identified. The shapes of the first 6 are the same as in figure 11. Resonant frequencies ranged from 255.8 Hz for the first mode to 3611.0 for the tenth mode.

The sub-sampling grid is 48×36 or 1728 pixels to serve as inputs to the neural net. Hence the training set requires 173 uncorrelated speckle patterns for each mode used in the training set. Mode four was selected as the mode to be monitored, and the first, third and sixth modes were selected for contamination and calibration. These modes were selected, because they can be measured conveniently by the heterodyne interferometer. Training over the full frequency range was accomplished with the second, fourth, fifth, seventh, eighth, ninth and tenth modes. The tenth mode also can be measured along the interferometer scan line, but was selected for training as the highest frequency mode in the set. The fourth mode was monitored at the center of the interferometer scan line. Its maximum excitation point is located elsewhere, and was estimated from the Bessel fringe pattern at 1270 nm peak to peak. This amplitude is a bit more than 2 waves. The excitation used for the model data discussed above was 6 waves.

Calibration curves were then generated from the first, third and sixth modes. These modes were excited using an eddy current exciter. The interferometer was used to determine the mode amplitudes as a function of drive voltage for peak-to-peak amplitudes of 20, 40, 80, 160, and 320 nm. The interferometer was then used to monitor the amplitude of the fourth mode, and the eddy current voltage was used to set the amplitudes of the contamination modes. Visualization of the real-time characteristic patterns was used to assure that the tests were performed at resonance.

Figure 12 shows the three calibration curves for contamination by the first, third and sixth modes at 255.8, 914.0, and 1575.0 Hz respectively.

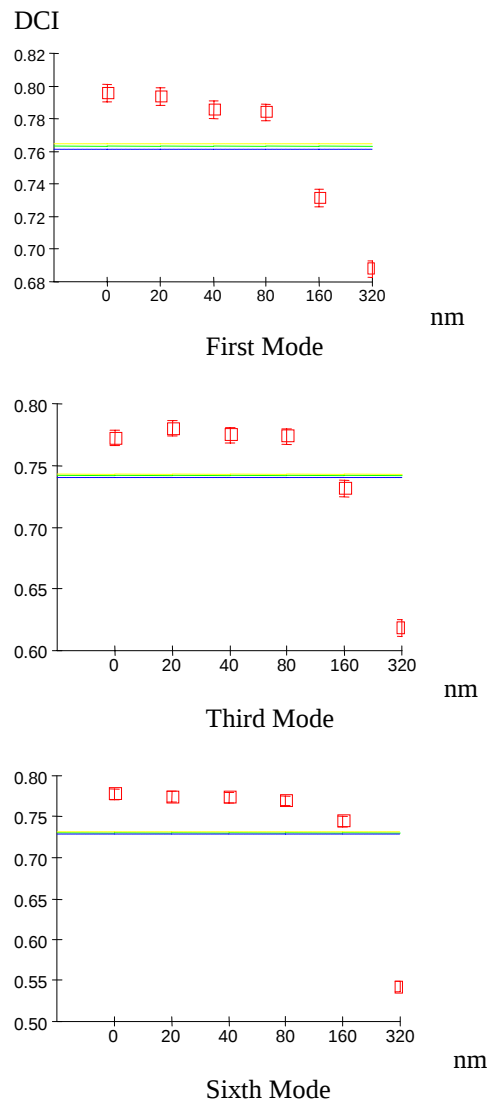


Figure 12.—Experimental calibration curves.

Discussion of Results of the Experimental Test of the First Implementation of the Optics-Only Calibration Procedure

The use of more modes for training has improved the sensitivity greatly and made it more uniform. The sensitivity is about 100 nm peak to peak as shown by figure 12. The best sensitivity of the model trained net was 160 nm peak to peak as shown by figure 6. The current resolution is 1728 input pixels versus 903 input pixels for the model trained net. The resolution dependence of sensitivity has also been noted for the calibration technique based on torque variation.³ The sensitivity for mode 6 appears to be slightly less than for the other modes, but there is not the drastic difference that was noted in an earlier test using fewer training modes.

The Performance of the Second Implementation in an Experimental Environment

An attempt was made to achieve the sensitivity improvement already observed in figure 9 for the model-trained net. Both modes of the mode pairs were excited with eddy current exciters, rather than a siren, eddy-current combination, in an attempt to minimize the amplitude fluctuations. The exciter for the fourth mode was placed near the center of the plate, and the exciter for the contamination modes was placed near the upper left. The contamination modes used for training were excited at 80 nm peak to peak. It was necessary to restrict training and testing to those contamination modes that could be measured along the scan line of the heterodyne interferometer.

In general, the sensitivity of the nets trained with folded data was too great for the noise level of the current test environment. This can be seen using the results from one test. The fourth mode was selected for monitoring. The fourth mode was contaminated with the third and sixth modes, each at 80 nm peak-to-peak for training. The sub-sampled patterns were transformed with 5 folds each for training.

The net learned the training set very easily, even with only 6 hidden-layer nodes. Easy learning in this case is very suspicious. It implies that the net is using the enhanced sensitivity of the folding method to learn environmental fluctuations. The suspicion is confirmed by examining a box plot in figure 13 of the response of the net at sixth-mode levels of 0, 20, 40, 60, and 80 nm. Note that 0 and 1 in the plot represent an amplitude of 0. The designation 1 was a repeat of the 0-amplitude case at the end of the experiment. Figure 13 shows that the test outputs are spread over the entire output range of the neural net. By contrast, a box plot of the first-implementation data in figure 14 shows that the outputs are spread over only a fraction of the net output range. The numbers in the plot are outliers. Figure 14 begins at 0.4 rather than 0.2 to enhance the spread.

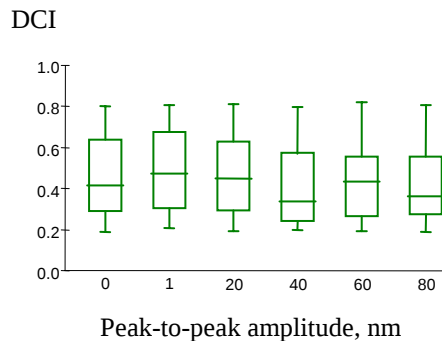


Figure 13.—Box plot of folded experimental data for sixth mode showing that data cover entire neural-net output range of 0.2 to 0.8

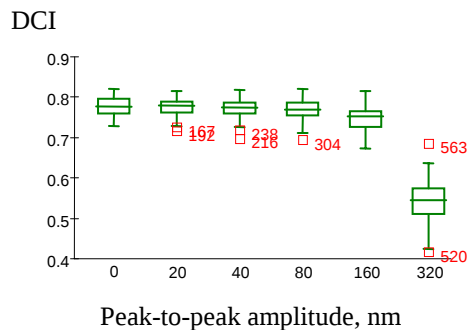


Figure 14.—Box plot of first implementation data; numbers in plot represent outliers; data are for sixth mode contamination.

Concluding Remarks

The optics-only calibration processes are excellent ways to characterize the sensitivity of the neural-net NDE method and to measure improvements in that method. There is no need to modify the structure being tested in any way to use the calibration processes. The processes can easily be used to characterize the state of the measurement environment and any improvements resulting from a modification of that environment. Model generated data supports the earlier conclusion that the limiting sensitivity of the neural-net technique is around 10 nm. That is, damage that causes the relative mode shape to change by 10 nm might barely be detectable. But all other random effects must be eliminated or the net must be trained to ignore them.

A single representative calibration curve can be generated, if enough modes are used for training and calibration. A customer oriented calibration service requires a more convenient means for measuring vibration-mode maximum amplitudes, but there are commercial instruments available to accomplish said measurements.

In addition to demonstration applications, future work should include research to better minimize the effects of the environment. One approach is to use higher frequency modes. The exposure time can be reduced, so that lower frequency building noise, air currents and optical fluctuations are rendered less important.

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13. ABSTRACT (Maximum 200 words) A calibration process is presented that uses optical measurements alone to calibrate a neural-net based NDE method. The method itself detects small changes in the vibration mode shapes of structures. The optics-only calibration process confirms previous work that the sensitivity to vibration-amplitude changes can be as small as 10 nanometers. A more practical value in an NDE service laboratory is shown to be 50 nanometers. Both model-generated and experimental calibrations are demonstrated using two implementations of the calibration technique. The implementations are based on previously published demonstrations of the NDE method and an alternative calibration procedure that depends on comparing neural-net and point sensor measurements. The optics-only calibration method, unlike the alternative method, does not require modifications of the structure being tested or the creation of calibration objects. The calibration process can be used to test improvements in the NDE process and to develop a vibration-mode-independence of damage-detection sensitivity. The calibration effort was intended to support NASA's objective to promote safety in the operations of ground test facilities or aviation safety, in general, by allowing the detection of the gradual onset of structural changes and damage.				
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